Plasma Chemistry & Plasma Loading in an HPRF Cavity

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Processes

- There are four main processes associated with the HPRF cavity:
  - Plasma formation

    &
  - Electron – ion interactions
  - Electron – neutral interactions
  - Ion – ion interactions

Plasma Formation

- The number of electron – ion pairs produced by a beam can be calculated

$$N_{pairs} = \frac{dE/dx \;\rho\; L}{W_i} N_{beam}$$

dE/dx = stopping power
ρ = gas mass density
L = beam path length
W_i = avg. molecular ionization energy

Parameter	Units	MTA Beam (protons)	HCC Beam (muons)
Momentum (KE)	MeV / c (MeV)	956 (400)	200 (121)
Gas	-	H_2 + Dry Air	$H_2 + O_2$
Dopant concentration	%	5	1
dE/dx	MeV cm^2 / g	6.332	4.148
ρ	g / cm^3	0.00867	0.015
W_i	MeV	36.2	36.2
Bunch population	# / bunch	2 x 10^8	1 x 10^{12}
N_{pairs} / L	# / cm / bunch	3.50 x 10^{11}	1.88 x 10^{15}

Plasma Formation – II

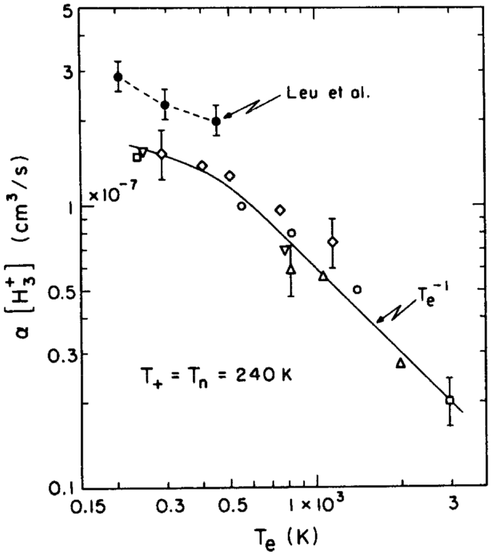
- Through collisions with gas molecules, electrons come into equilibrium (above room temperature) and drift with the RF field
  - Collision frequency: 64 x 10^{12} s^{-1} at 180 atm (30 ps equilibrium time)
  - Plasma frequency: 6.9 x 10^{12} s^{-1} (for 1.5 x 10^{16} e^-/cm^3)
- The ions remain in thermal equilibrium with the surrounding gas
- The amount of energy dissipated, or "plasma loading" can be evaluated:

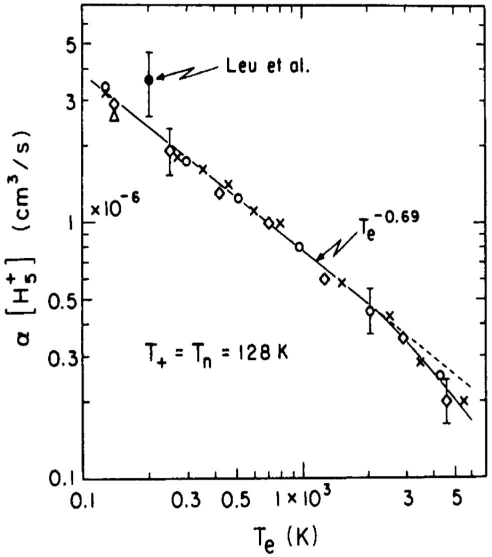
$$dw = q\int v\,E_0 \sin(\omega t)\,dt = q\int \mu\,E_0^2 \sin^2(\omega t)\,dt$$

$$v = drift\ velocity \quad \mu = mobility$$

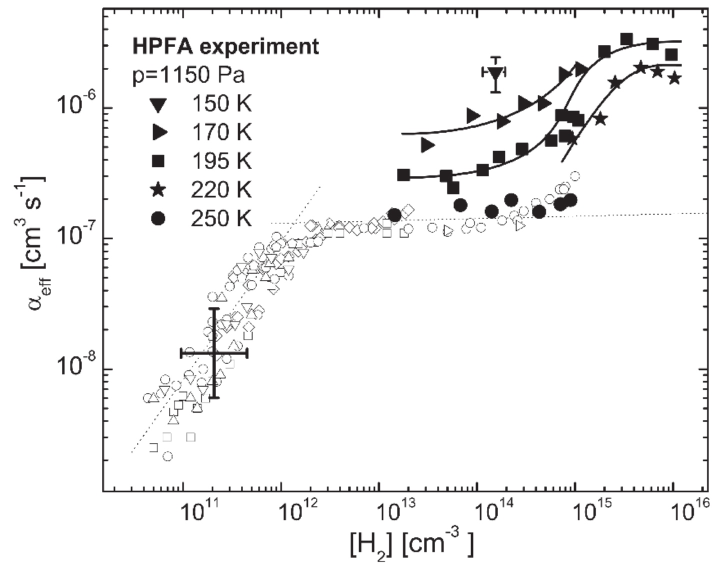
Electron – Ion Interactions

- Electrons may recombine with the hydrogen ions formed (H^+, H_2^+, H_3^+, H_5^+, H_7^+...)
- We had no way of distinguishing the ion cluster, and so measured an effective rate
- Our measurements are on the order of 10^{-7} – 10^{-6} cm^3/s, consistent with Literature measurements of H_3^+ and H_5^+
- ***Recombination rates tend to increase with gas pressure***





Macdonald et al, Planet Space Sci., Vol. 32, No. 5, 1984



Glosik et al, Plasma Sources Sci. Technol. 12 (2003)

Electron – Neutral Interactions

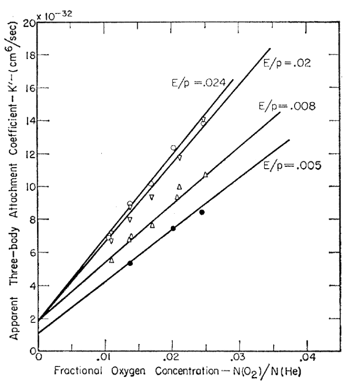
- Electrons can become attached to O_2 in three-body reactions, that at high densities look like two-body reactions

$$e^- + O_2 \rightarrow O_2^{-*}$$

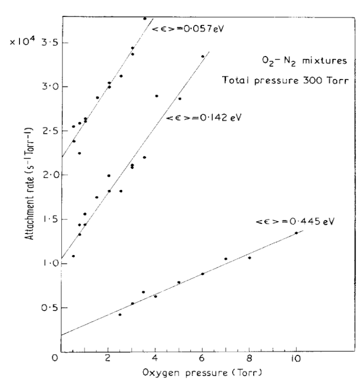
$$O_2^{-*} + M \rightarrow O_2^- + M$$

$$O_2^{-*} + M \rightarrow e^- + O_2 + M$$

- The identity of the third body is important in the attachment process, and has been measured in great detail for N_2 and O_2, but not for H_2



Chanin et al, Phys. Rev., Vol. 128, No. 1, 1962



McCorkle et al, J. Phys. B: Atom. Molec. Phys., Vol. 5, June 1972

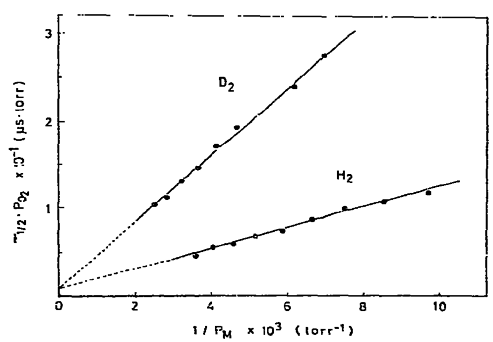


Fig. 4. $\tau_{1/2}P_{O_2}$ versus $1/P_{H_2}$, $1/P_{D_2}$ (P_{O_2}/P_{H_2} = 0.0188, P_{O_2}/P_{D_2} = 0.00217).

Shimamori and Hatano, Chem. Phys. Lett., Vol. 38, No. 2, 1976

B	k_a, 10^{-30} cm^6/s	p, torr
	$A = O_2$	
O_2	2,4±0,1	30—300
	2,2±0,2	100—400
	2,6±0,1	250—600
	2,8	7—55
	2,0±0,2	10—500
	3	3—30
	2,12±0,14	1—10
	2,2±0,1	2—100
	1,7	10—100
	2,1±0,2	1—150
	2,2	5—25
He	0,033±0,003	160—425
	0,028	7—55
	0,076	1—150
Ne	0,023±0,003	90—300
Ar	0,05±0,01	100—300
Kr	0,05±0,01	60—200
Xe	0,085±0,005	35—170
N_2	0,085±0,003	30—300
	0,5	15—150
	0,26	10—100
	0,11	1—150
	0,11	5—20
H_2	0,48±0,03	100—300
D_2	0,140±0,005	140—400
H_2O	14±5	250—600

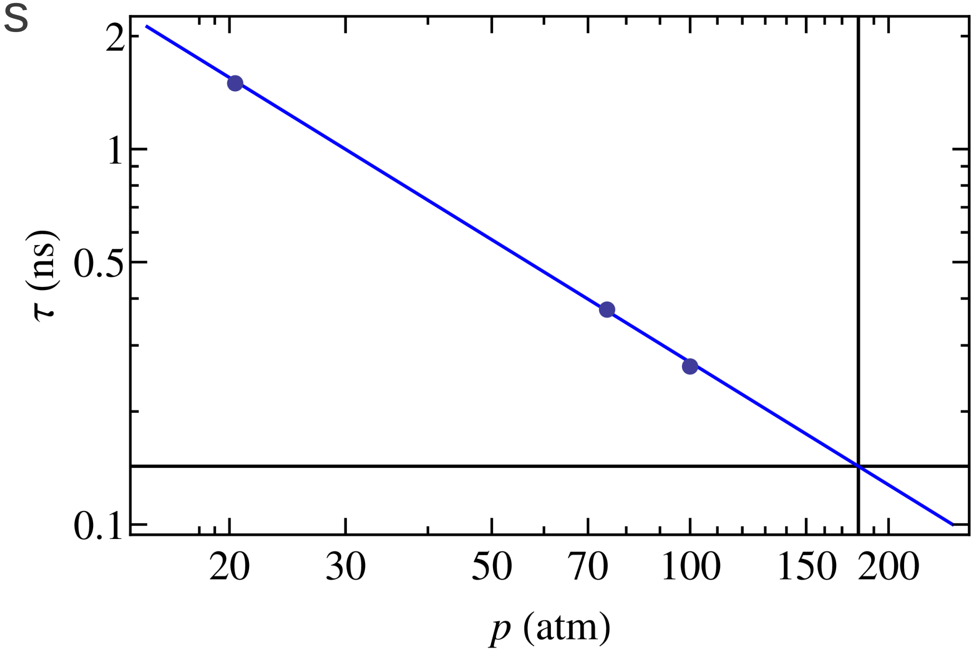
Aleksandrov, Usp. Fiz. Nauk., 154, Feb. 1988

Electron – Neutral Interactions II

- Our third bodies are mostly H_2, with some N_2 and O_2
- The rate equation for electrons is:

$$\frac{dn_e}{dt} = \dot{N} - \beta\, n_e n_{H^+} - \frac{n_e}{\tau} \qquad \beta\, n_e n_{H^+} = \sum_l \beta_l n_e n_{H_l^+} \qquad \frac{n_e}{\tau} = \sum_M k_M n_e n_{O_2} n_M$$

- Using our measurements of the recombination rate in pure hydrogen and energy loss per electron-ion pair, the measured power loss can be fit to give the attachment time of electrons
- On the right are the extrapolated attachment times for H_2 doped with 1% dry air at an E/P = 20 MV/m / 180 atm
- The prediction at 180 atm is 142 ps



Ion – Ion Interactions

- Because the electrons go away so fast, ions play a significant role in plasma loading
- No work has been done on hydrogen-oxygen ion recombination, however other ions have been studied
  - Rates fall with E/P
  - Above 1 atm, rates fall with with P
- Our data shows similar trends – the ion-ion recombination rate predicted is on the order of 10^{-9} cm^3/s at 180 atm and 20 MV/m
- This is not fast enough to negate the ions within a beam pulse
- Luckily ions load the cavity ~100 times less than electrons

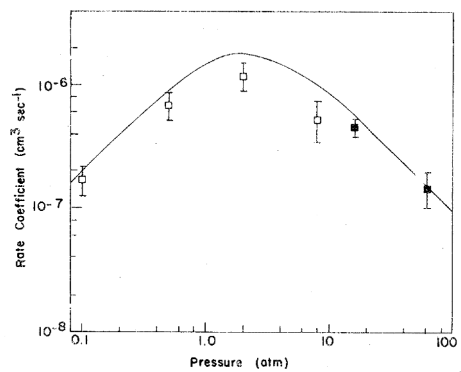


FIG. 4. $Kr^{+}+F^{-1}$ Ar recombination-rate coefficient. Solid line is curve (2) from Fig. 1. Points □ are MD calculations for $n_i = 10^{13}$ cm^{-3} using MD option (iii) (see Sec. IV of text). Points ■ are MD calculations for $n_i = 10^{15}$ cm^{-3} using MD option (iv).

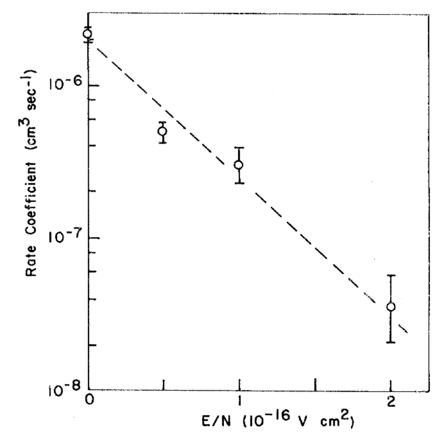
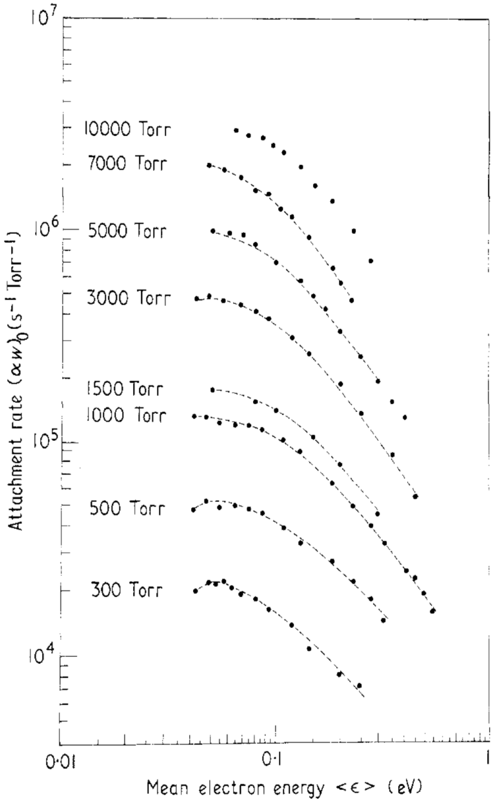


FIG. 6. $Kr^{+}+F^{-}$ He recombination-rate coefficient vs discharge E/N for $P = 3$ atm and $n_i = 10^{15}$ cm^{-3}.

Morgan et al, Phys. Rev. A, Vol. 26, No. 3, 1982

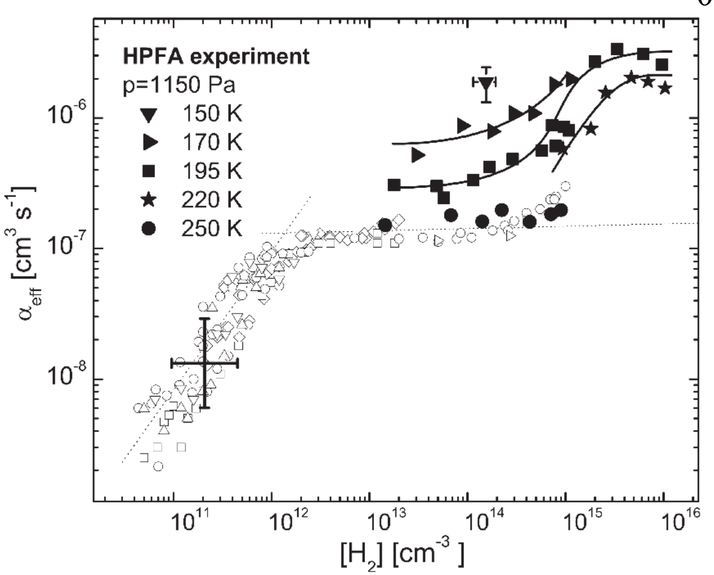
Pressure Effects

- It is known that gas and plasma density affects the mobility (drift velocity), recombination rate, and attachment rates



McCorkle et al, J. Phys. B: Atom. Molec. Phys., Vol. 5, June 1972

All effects are in the positive direction



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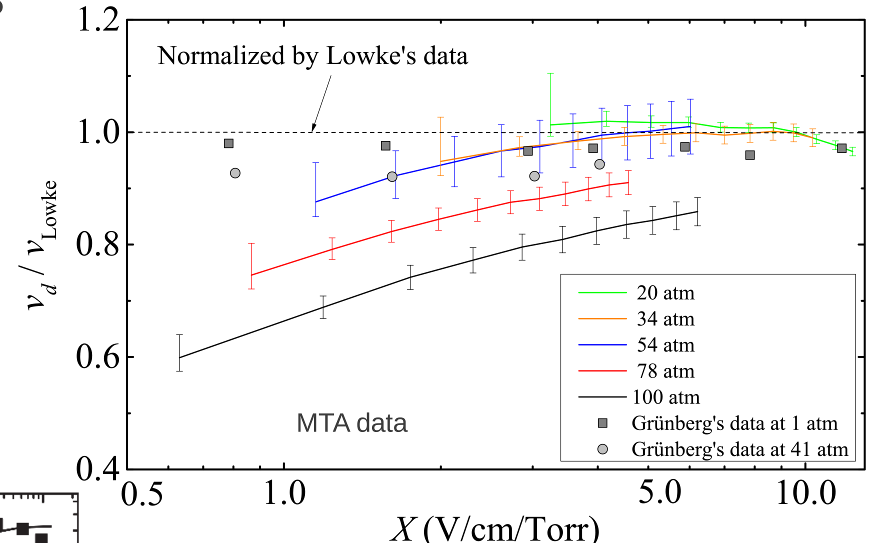
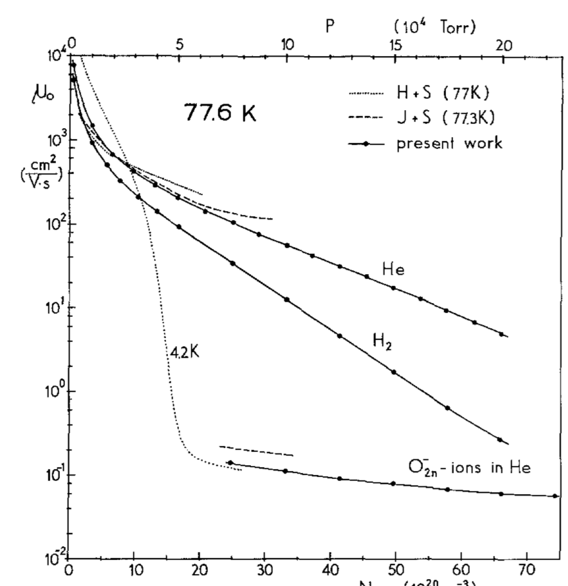




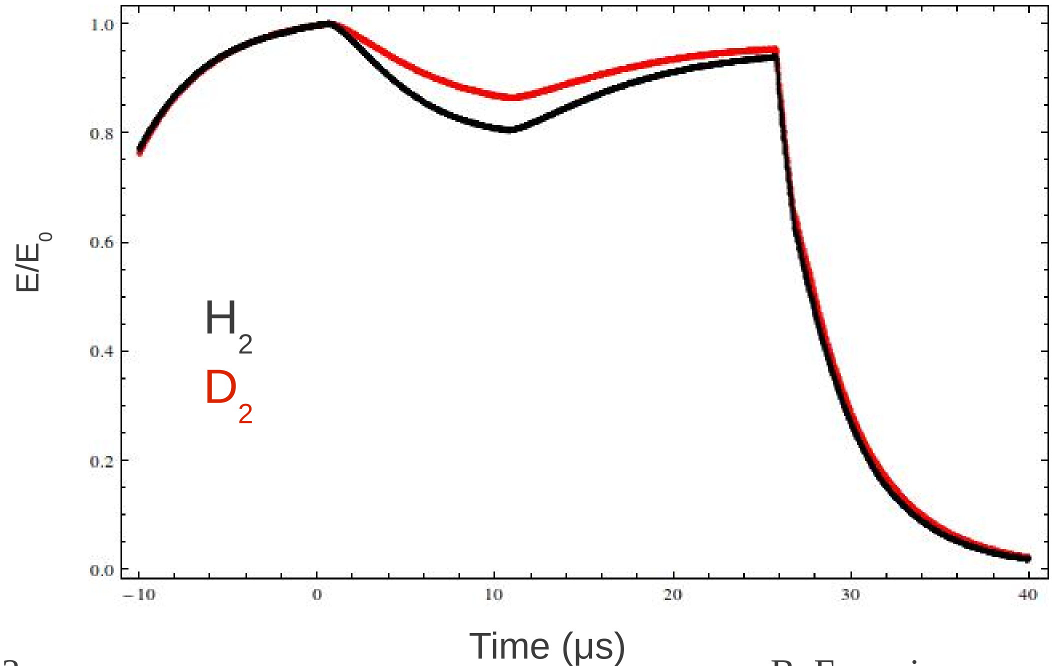
Bartels, Appl. Phys.8, 59-64, 1975

Gases Studied

- Energy loss and electron-ion recombination rates have been measured for the following gases:
  - H_2, D_2, He, N_2
- Electron attachment time and ion-ion recombination rates have been measured for the following gas combinations:
  - H_2+DA, H_2+N_2, H_2+SF_6, D_2+DA, He+DA, N_2+DA
- Due to its high boiling point, SF_6 would have to be used at room temperature
- The only suitable electronegative dopant appears to be O_2 – a small amount (~1%) does not significantly change the radiation length of the gas
- H_2 or D_2 appear to be the only candidates with suitable stopping power in the 200 MeV/c μ momentum range

Hydrogen vs Deuterium

- D_2 ions load the cavity less than H_2 ions due to their larger mass
- Initial results also indicate the ion-ion recombination rates for D_2 are larger than those for H_2
- Data was taken with only one gas pressure and one dopant concentration
  - More data is needed to reach any conclusions

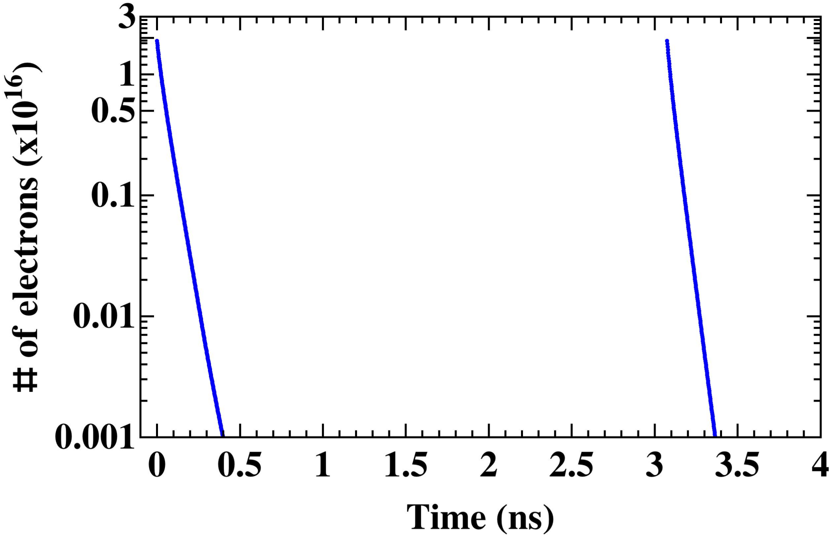


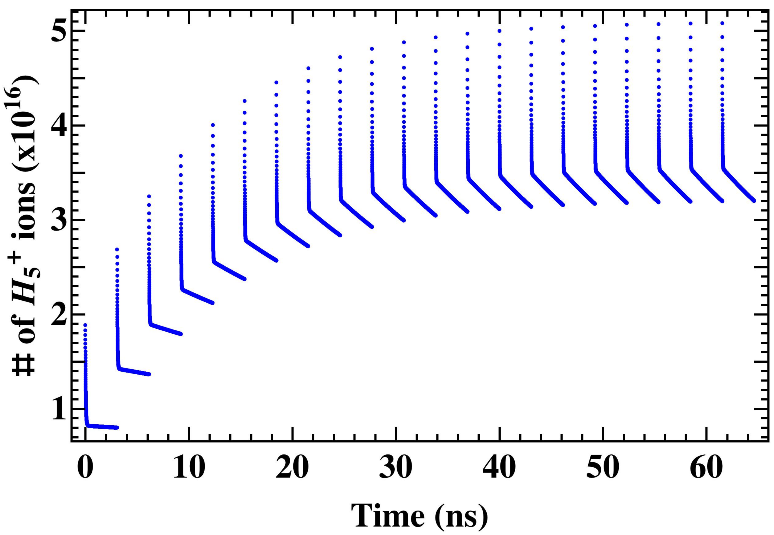
Plasma Loading Calculation

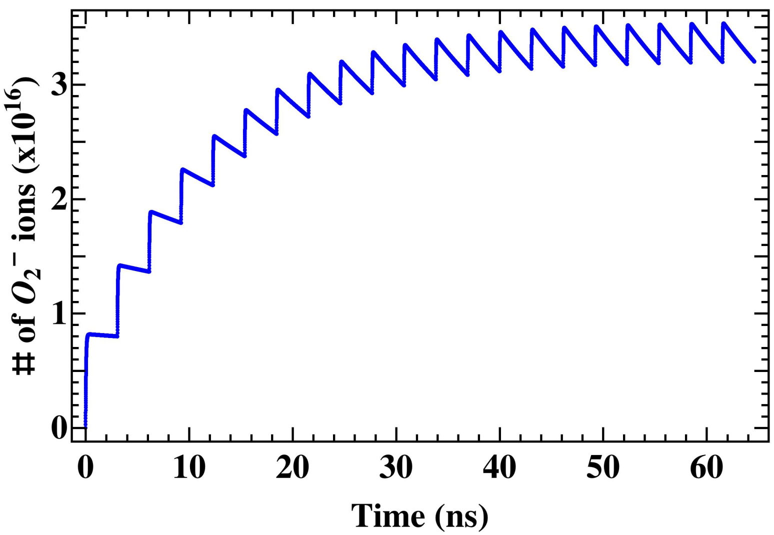
- Input parameters (derived from beam test data):
  - Electron attachment time
  - Electron – hydrogen recombination rate
  - Hydrogen – oxygen recombination rate
  - Electron drift velocity (constant)
  - Ion energy loss
- Assumptions:
  - 325 MHz bunched beam
  - 21 delta function bunches
  - 160^{o} injection (relative to RF)
  - 20 MV/m peak E field
  - 180 atm H_2 gas with 1% DA
  - 10 cm long cavity
  - Recombination rates constant (10^{-6} cm^3/s e-H, 10^{-9} cm^3/s O-H)
  - 1 cm^3 plasma volume (homogeneous density)
  - Attachment time varies with E field (100 ps min.)
  - Cavity voltage not affected by plasma loading

Plasma Loading Calculation Results

- The total number of each charged particle species is tracked over 21 beam pulses
- Electrons "decay" very quickly, however ions build up over time
- Time step is 1/1000 of an RF period
- 650 MHz RF, 10^{12} μ/bunch is shown







Plasma Loading Calculation Results – II

- Two RF frequencies and two bunch intensities were considered
- In all cases, plasma loading was minimal

Parameter	Unit	Value			
RF frequency	MHz	325		650	
Stored energy	J	19		4.7	
μ/bunch	#	10^{11}	10^{12}	10^{11}	10^{12}
Electron dissipated energy	J	0.014	0.072	0.012	0.062
Ion dissipated energy	J	0.010	0.029	0.020	0.059
Total dissipated energy	J	0.024	0.101	0.032	0.121
% of V_{accel} seen by last bunch	%	99.9	99.7	99.7	98.7

Conclusions

- Based on extrapolation of parameters measured during the MTA HPRF beam test, plasma loading appears to be minimal in a HCC
- The effects of higher gas and plasma densities must be investigated
  - All signs point to positive effects
  - Experimental data will be difficult to obtain
  - Simulation must be relied upon in the meantime